

# Characterization of Thermophotovoltaic Cells

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**Abstract** - Thermophotovoltaic (TPV) research has entered a period of rapid expansion after 30 years of effort, yet there is still no comprehensive method of TPV cell characterization. To support this increase in research, the Jet Propulsion Laboratory has developed many necessary procedures for TPV cell characterization. This low-cost, pioneering effort was made possible by utilizing or modifying available equipment. Simple procedures allow the derivation of temperature coefficients for  $V_{oc}$  and  $I_{sc}$ , as well as the intensity coefficient for  $V_{oc}$ . Specific standard spectra are used while both the source intensity and the cell temperature are adjusted. Measurements of cell external spectral response and dark forward and reverse diode current are used to further characterize the cell. Standard operating conditions of spectrum, intensity and cell temperature are proposed so that TPV cell performance and efficiency data will be universally accepted for cell comparison. Examples of TPV cell data are illustrated and a description of test apparatus is also presented. This cell characterization effort permits modelling the performance of a TPV cell in a total TPV system. In addition to system modelling, cell design and TPV cell material development efforts are also supported.

## INTRODUCTION

Thermophotovoltaic (TPV) research has now reached a period of rapid expansion after much effort over the past 30 years [1-3], yet no comprehensive discussion of TPV cell characterization is in the literature. This is probably due to early attempts using available photovoltaic (PV) cells and a consequent emphasis on system analysis and performance rather than cell performance. Now that TPV cell material and design research is coming into its own, cell testing is becoming more important.

Investigation of low bandgap (0.5-0.7 eV) PV materials, such as GaSb, InAs, InAlAs and InGaAs, is presently being pursued by many different organizations as part of an overall TPV cell development program. To support this increased research in TPV cell material development, the Jet Propulsion Laboratory (JPL) has developed many necessary procedures for TPV cell characterization. The characterization effort permits modelling the performance of a TPV cell in a total TPV system. In addition, subsets of full characterization results also support the cell design and cell material development efforts.

One example of the need for a specific TPV characterization effort is the problem that occurs when a TPV system efficiency is quoted. Questions of spectrum, intensity, cell temperature, heat losses, emittance, transmittance, etc. are immediately raised. Another example is the use of cell efficiency data alone. If a cell is measured as suggested below the cell efficiency is likely to be only 3-5%. However, this same cell when used in a TPV system with a selective emitter and spectral reflective filter may allow a system efficiency of 15%. To provide a basis for answering the questions and avoiding the efficiency confusion, the JPL TPV cell characterization methodology, including a proposed set of standard operating conditions for cell measurement comparison purposes, is discussed below.

## CHARACTERIZATION METHODOLOGY

Comprehensive characterization is even more important for TPV cells than for photovoltaic (PV) cells. PV cells are used in environments with various temperatures and insolation intensities. However, the light spectrum is essentially the same, the sun in space (AM0) or on Earth (AM1.0 or AM 1.5). TPV system designs are being pursued where major spectrum modification, at the system operating point, is assumed as well as spectral shifts during off-nominal operation. Since TPV cells will be made from low bandgap materials, the voltage temperature coefficient and the cell operating temperature range are more important than in higher bandgap PV cells. High intensities are the general case in TPV systems, making it essential to have an intensity coefficient and a knowledge of cell resistances. Without suitable cell data, it is impossible to accurately model the effects of intensity, spectral and temperature changes on system performance.

TPV cell characterization can be broken down into two main interest areas: Characterization for TPV systems modelling; and characterization

for cell material and design improvements. Due to an interest in power system applications for spacecraft, the focus at JPL has been on TPV cell characterization for system modelling. Organizations with a prime interest in cell material and design improvements would have an installed capability for cell material characterization for parameters such as minority carrier lifetime, wafer dislocation density, doping level determination, etc. Therefore, the discussion below focuses on four areas of characterization for system modelling needs: TPV Cell performance; TPV system operating conditions; TPV cell physical parameters; and TPV cell quality control.

### **TPV Cell Performance Characterization**

Distinct TPV system designs will result in cells operating under different emission spectra and intensities depending upon the source emitter characteristics and temperature. It can be argued that a single emission spectra IV curve and a spectral response curve should be sufficient for cell performance characterization under different emission spectra. However, since the spectral response is usually taken at a relatively low intensity and the cell is operated at a much higher intensity, the correct intensity corrections may not be known. Also, one would expect the various temperature coefficients to vary with intensity, emission spectra, and range of temperature. In addition, actual TPV system implementations may have an off-nominal operation requirement causing cell performance to change.

TPV Cell performance characterization requires at least the three following tests:

- 1) IV curves under certain standard operating conditions of emission spectra, emission intensity and cell temperature;
- 2 ) IV curves under various emission spectra over a range of emission intensities and cell temperatures; and
- 3) Spectral response curves over a range of cell operating temperatures.

These tests allow the derivation of voltage, current and power temperature coefficients and other cell parameters, under different emission spectra and permit the complete performance comparison and characterization of each type of TPV cell over a range of emission spectra and operating conditions. The reasoning behind this TPV cell characterization approach is detailed below.

### ***IV Curves at Standard Operating Conditions (SOC)***

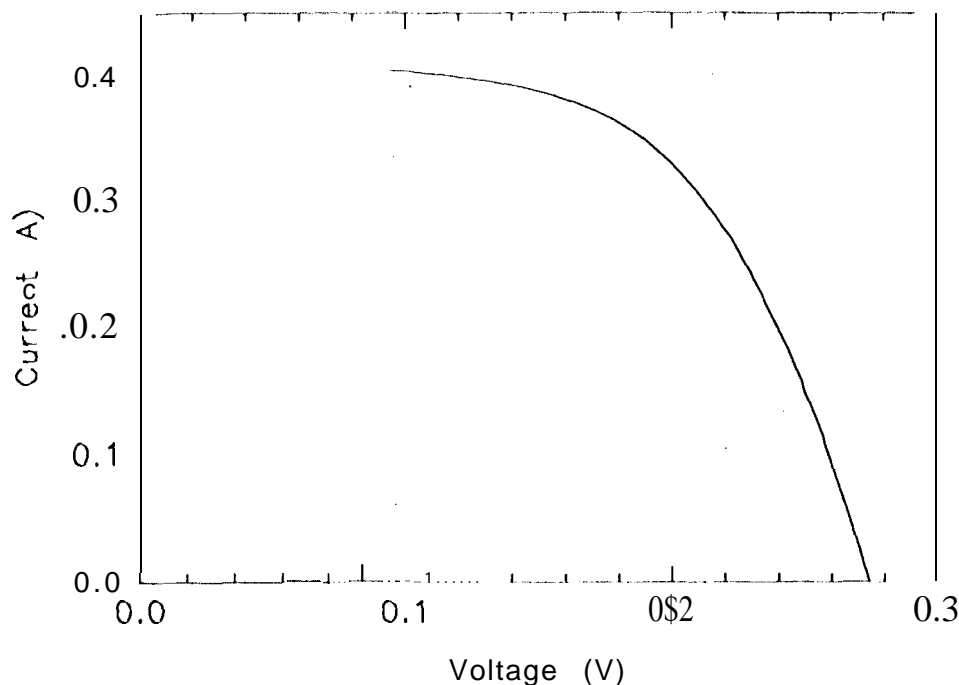
In order for TPV cell performance characterization and efficiency data to be widely accepted, a universally approved SOC specifying a standard emission spectra, emission intensity and cell operating temperature must be adopted. Perhaps more than one set of SOC will be adopted, particularly if TPV cells were to be classified according to their bandgap or system operating temperature range. The need for specifying OaCh of the three parameters will be discussed below.

Using a selective wavelength emitter to measure the IV characteristics of a TPV cell will not provide reliable data for the accurate prediction of cell performance under another emission spectra. This is true because measuring the emission spectra of such an emitter is a difficult task and is prone to measurement error. The emitter surface and material properties must be known in detail, including how the emitter surface changes with time, contamination and roughness and how the emittance changes with temperature. The choice of a standard emitter or emission spectra for the characterization of TPV cells must, therefore, be universally accepted and predictable.

A black body is such an emitter, and it is presently used as a standard for comparing radiation characteristics. The emission spectra of a black body is dependent only on its temperature and can be accurately calculated by using Planck's equation. In addition, black body sources are readily available which enables comparable TPV cell measurements to be made at other laboratories.

For example, if a low temperature TPV system operated as a black body emitter at 1255 K, it would emit about 14 W/cm<sup>2</sup> (more than 100 suns equivalent). However, it is unlikely that a TPV system will ever have the perfect emissivity of a black body and the intensity is reduced further by the use of selective emitters and band pass filtering. To allow for these effects the distance between a 1255 K black body aperture and the cell is adjusted to achieve some standard intensity value, perhaps 2 W/cm<sup>2</sup>, as a reference point.

A test of this kind is easily achieved in the laboratory and would result in cell output versus a standard grey body emitter of the same temperature as the black body and an effective emittance of 0.143. An example of an IV curve taken at JPL using a 1200 C black body source with the cell located at a distance to produce 2 W/cm<sup>2</sup> intensity is shown in Figure 1.



**FIGURE 1.1200 C** Black body IV curve for TPV cell,

Low bandgap TPV cell performance is highly sensitive to temperature which influences cell voltage and power output. Use of a cell operating temperature of 20 C results in a moderate system efficiency as a reference point under the 2 W/cm<sup>2</sup> intensity. This temperature is simply achieved in the JPL PV laboratory by using a recirculating water bath coupled to a water cooled test head. A temperature rise of only 2 C was measured between the cell and the cooling water at an intensity of 1.2 W/cm<sup>2</sup>. For this measurement the cell junction temperature was obtained by first measuring the cell resistance as a function of cell temperature while the cell was not illuminated. Cell resistance during illumination was then measured by using a shutter and rapidly switching test circuits.

### ***IV Curves Over a Range of Temperature versus Intensity***

TPV cells are very similar to solar PV cells, except they will be operating at high power density levels, longer wavelengths, and over a limited cell temperature range. The actual power density will depend

upon the TPV system design but is likely to be in the range of 100 to 500 suns for a commercial high temperature TPV system (1 600 K to 2000 K) or 10 to 100 suns for a low temperature radioisotope heated TPV system (1000 K to 1500 K). Even if a TPV system had the perfect emissivity of a black body, this emission would have to be modified by a filter before reaching the cell in order to achieve high conversion efficiency. Therefore, system designs with selective emitters or band pass filters may result in lower emission intensities. Thus, at selected black body temperatures, the intensity must be varied by adjusting the black body aperture to cell distance. The result is a family of cell output versus grey body emittance levels.

As is true with concentrator PV cells, TPV cell series resistance and cell temperature have a non-linear influence upon cell current and power output. In addition, cell temperature markedly influences cell voltage and power output. Therefore, it is necessary to test the TPV cells at selected cell temperatures while varying black body temperature and intensity. This provides a full characterization and allows the calculation of current, voltage and power temperature coefficients as determined by JPL and shown in Figures 2, 3 and 4. A good discussion of PV material coefficient determination is found in Reference 4.

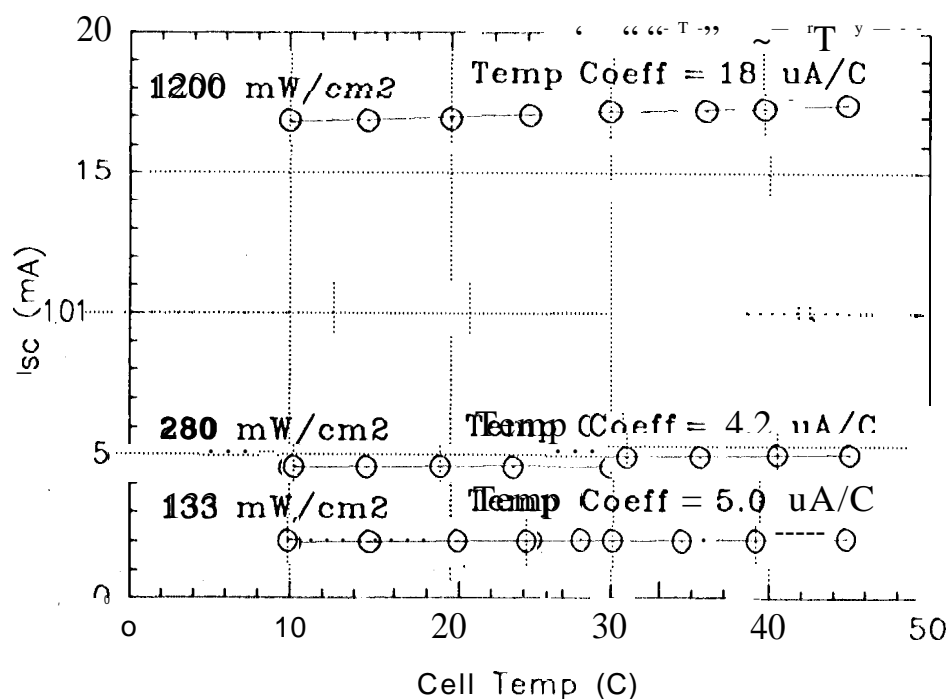


FIGURE 2. Isc versus cell temperature and intensity for GaSb TPV cell.

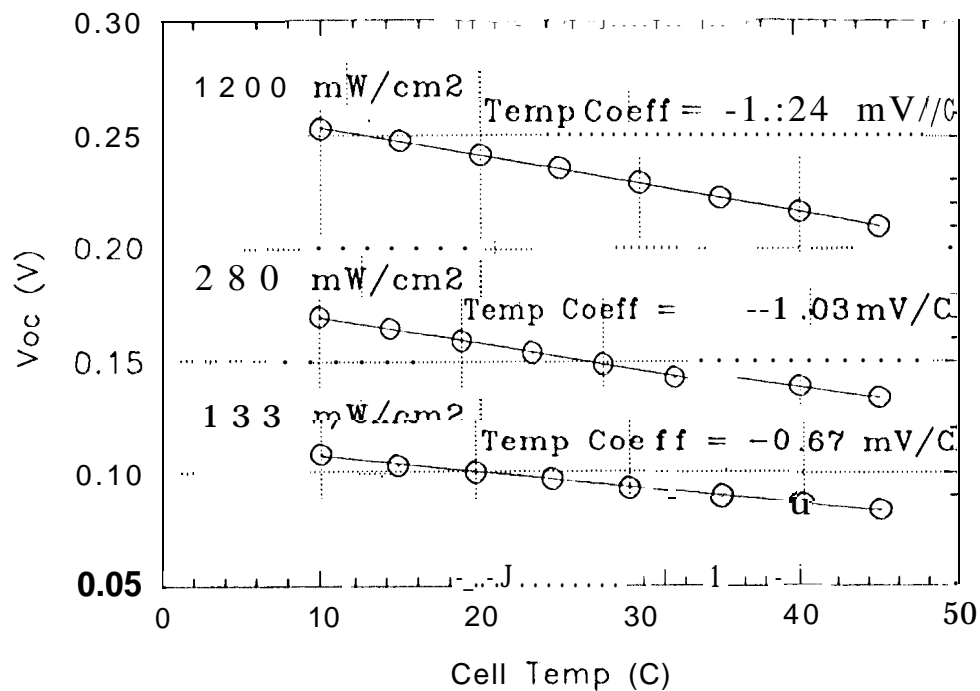


FIGURE 3. Voc versus cell temperature and intensity for GaSb TPV cell.

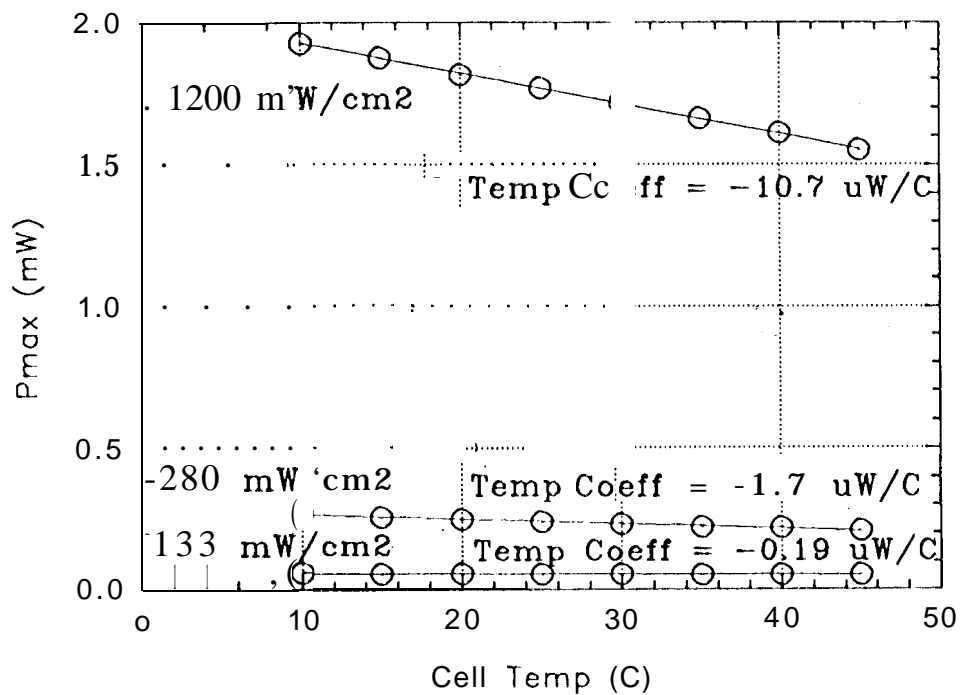


FIGURE 4. Pmax versus cell temperature and intensity for GaSb TPV cell

## *Spectral Response*

The spectral response of a cell changes with temperature, therefore, this measurement should be made over a range of temperatures or at least at the high and low end of the temperature range. Expected cell short circuit current ( $I_{sc}$ ) can be computed for each temperature by integrating the spectral response with a black body emission spectra or a selective emission spectra.

A full IV curve for use in system modelling can then be developed by using this data along with other cell characterization data. In addition, this measurement can be used along with IV tests to aid in discovering the effect of radiation testing or stability testing upon the cell performance.

Spectral response is also a useful analytical tool for cell fabrication since the cutoff frequency is a prime indicator of bandgap energy. Examples of spectral response curves for InGaAs TPV cells with different iridium and gallium percentage compositions and thus different bandgaps were obtained by the JPL Standards Laboratory and are shown in Figures 5 and 6.

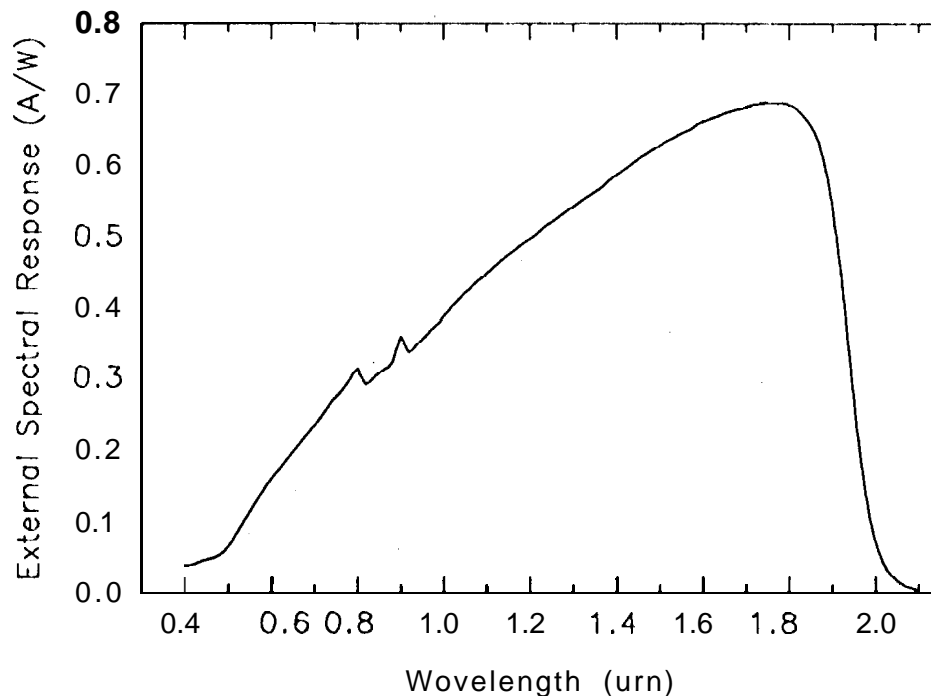


FIGURE 5. Spectral response for InGaAs TPV cell #1.



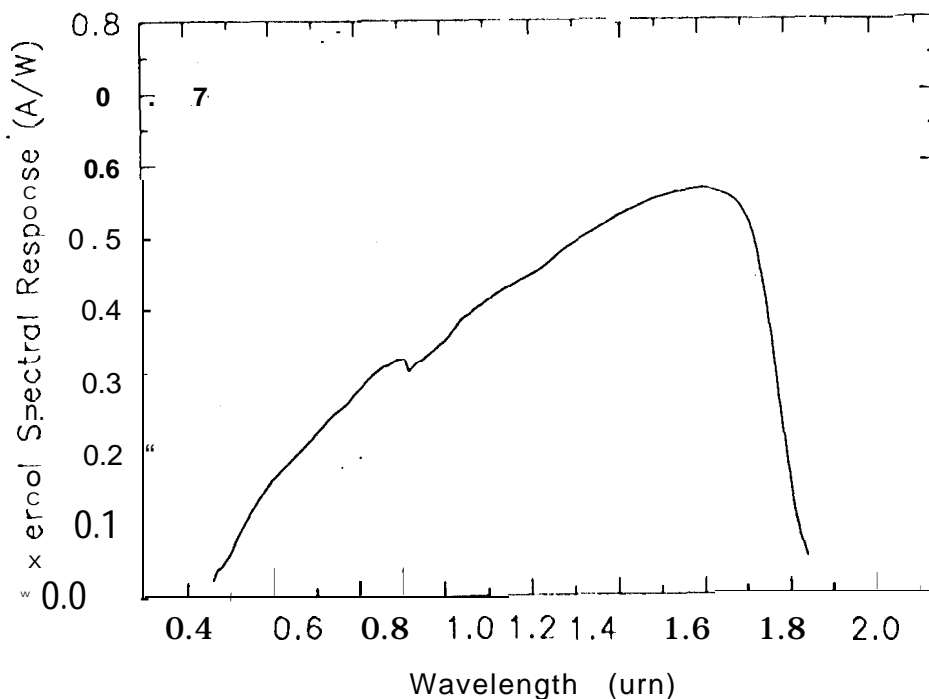


FIGURE 6. Spectral response for InGaAs TPV cell #2,

### TPV System Operating Conditions Characterization

The aforementioned tests only involve the testing of TPV cells under ideal conditions. However, the actual conditions for cell operation in a system should be taken into account, since they could have major influence upon system performance. TPV system operating conditions characterization require at least the following three tests:

- 1 ) Measuring the light and dark reverse IV curves;
- 2) Determining cell radiation sensitivity; and
- 3) Evaluating Cell Stability.

#### *Light and Dark Reverse IV Curves*

The light and dark reverse IV curves allow researchers to anticipate the effects of a partially inoperative cell, possibly due to breakage, in an array of TPV cells. The light reverse curve shows the combination of cell diode current and light generated current versus reverse bias voltage. The dark reverse curve only shows the cell diode current versus reverse

bias. An inoperative cell acts like a resistor in the cell array. Current is forced through the inoperative cell by the operating cells forcing a reverse bias to appear across the inoperative cell. Depending upon the reverse characteristic of the cell, the result could be a significant rise in temperature of the inoperative cell causing possible damage to the cell or TPV system. An example of a dark reverse IV curve is shown with its companion dark forward curve in Figure 7.

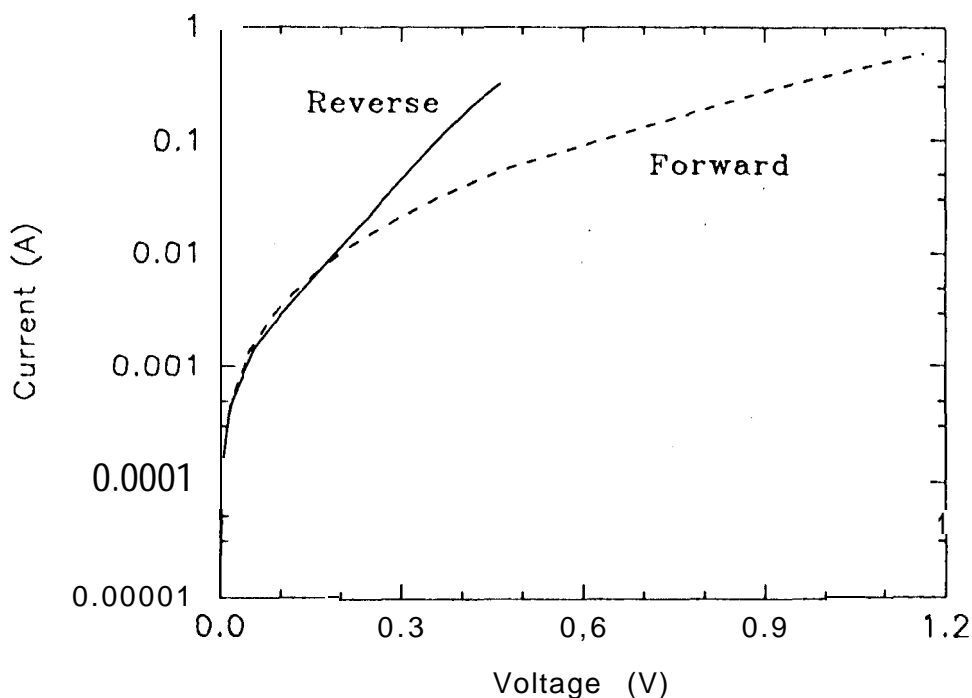


FIGURE 7. Dark current as a function of voltage.

### *Cell Radiation Sensitivity*

Cell radiation sensitivity is an important factor for TPV cells operating with radioisotope or nuclear reactor heaters. These power sources can emit beta, gamma, and neutron radiation which leave damage tracks in solid state devices. Under such circumstances, the effects of radiation on TPV cells must be determined just as they are for PV cells, except that neutron and gamma radiation is required instead of electron and proton radiation. Radiation sensitivity testing involves irradiating the TPV cells in a stepwise manner and measuring cell spectral response and cell performance at SOC. The data is then compared to initial cell performance data taken at SOC before the irradiation.

JPL has outstanding electron, beta and gamma radiation facilities. Furthermore, JPL has access to a radiation beam line at the California Institute of Technology for a broad energy spectrum proton source. Thus, JPL is capable of testing for the effects of electron, beta, gamma and proton emissions on cells, if necessary. While JPL does not have a neutron source, neutron radiation testing is conducted on a collaborative basis by an outside radiation source.

While JPL has excellent radiation testing facilities, there has been no radiation testing of TPV cells at JPL, due to time and funding limitations.

### *Cell Stability*

Cell stability testing at the JPL PV lab involves testing cell performance before and after exposure to environmental tests, such as continuous illumination, temperature soaking, temperature annealing or temperature cycling. Cell stability testing involves subjecting the cells to one or a combination of the above environmental tests in a stepwise manner and measuring cell spectral response and cell performance at SOC. The data is then compared to initial cell performance data taken at SOC before the test.

### **TPV Cell Physical Parameter Characterization**

Besides testing for operating characteristics and systems modelling, TPV cell physical parameter data must be taken so that later comparisons can be made accurately. While the physical cell data seems trivial, it has often been found to be invaluable in settling questions of whether active area or total area was used in an efficiency determination.

Collecting the physical parameter data involves determination of the following data:

- 1) Cell size, type, and structure;
- 2) Metallization pattern dimensions and resistance;
- 3) Calculation of total area, active area, and shadow area;
- 4) Measurement of cell back surface reflectivity versus wave length.

Except for the measurement of the cell back surface reflectivity, which is still under consideration, the remaining physical parameters are easily

measured with standard laboratory instruments or perhaps obtained from the cell fabricator. If contact resistivity is of interest then a special test pattern is required.

### **TPV Cell Quality Control Characterization**

TPV Cell quality control requires at least some of the following tests:

- 1) Carrier characterization;
- 2) Bandgap measurement; and
- 3) Dark forward diode current.

TPV system designs require the cells to operate in an intensity range of 10-500 suns, and therefore, to have low internal series resistance and relatively high internal shunt resistance. These characterization tests would provide some initial information about cell conformance" to these requirements before more characterization is performed. Essentially, if the cell does not perform favorably, then further cell processing and testing would not be necessary. The TPV cell quality control characterization approach is detailed below.

#### ***Carrier Characterization***

One approach to carrier characterization provides a majority carrier profile of the process wafer or cell cross section to determine the quality of the cell diode junction. A Polaron system is used at JPL for quality control at the wafer level. Cell level tests could also be of value, however, the shortage of cells has prevented use of this destructive test on cells at present. There are minority carrier concentration test approaches which are not destructive. This capability is not available at JPL, but maybe available at the National Renewable Energy Laboratory (NREL).

#### ***Bandgap Measurement***

At JPL bandgap measurements are made by two different methods - X-ray diffraction and photoluminescence. The X-ray diffraction technique is preferred in the early material development stage since it gives a better answer with less than optimum surfaces. Photoluminescence bandgap measurement is therefore is used as a check or later when there is production volume.

## ***Dark Forward Diode Current***

The current is measured as a function of forward bias voltage while the cell is not illuminated. When a cell has excessive internal series resistance, or if it is a quality cell operating at high intensity, then the dark diode current will be relatively high. This, in turn, causes the short circuit current ( $I_{sc}$ ) to be a similar amount less than the actual light generated current. An example of a dark forward IV curve measured at JPL together with its related dark reverse curve was shown in Figure 7.

The dark diode current is a strong function of temperature which argues for it to be measured at different temperatures resulting in a family of dark forward IV curves. Measurement at temperature has not yet been done at JPL due to time limitations, but is easily done using present water cooled test head and water bath equipment.

## **EXPERIMENTAL CAPABILITIES**

JPL is pioneering TPV cell characterization because of its unique combination of lengthy experience with PV cells and its specialized facilities. JPL has over 30 years of experience with PV cells and radioisotope power systems. This experience has resulted in the existing facilities which are available for use in the TPV cell characterization program. These facilities have been mentioned above and include:

- A) Large Area Pulsed Solar Simulator (LAPSS);
- B) Infrared Sensor Characterization Laboratory (IR Lab);
- C) Photovoltaics Laboratory (PV Lab); and
- D) Radiation Effects Laboratory (Rad Lab).

These facilities and their appropriate characterization tests are discussed in more detail in the following sections.

### **LAPSS**

The LAPSS consists of a solar illuminator, pulse forming network, control console, terminals, printer/plotter and a computer. The LAPSS equipment and computer program has been modified to incorporate TPV cells and the use of a black body emission source. To vary the cell operating temperature, a water cooled test head is used. By changing the temperature of the test head cooling water, the cell temperature is changed. Water temperature is monitored and the IV curve is taken when the water temperature has stabilized.

A standard black body with an operating range of 200 C to 1200 C (473K to 1473K) and a 0.99 emissivity is being used for the present test program as reported in Reference 5. This only allows for testing in the longer wavelengths for low bandgap cells. This is sufficient for the present task of characterizing the TPV cells being developed at JPL. Testing of higher bandgap TPV cells would require higher temperature black body emissions. This could be simply achieved by procuring a black body with a greater temperature range.

### **PV Lab**

The PV laboratory possesses the experience and facilities to conduct many of the characterization tests. This includes the testing for the dark forward and reverse IV curves, cell stability and cell metallization. Special mounting fixtures are available, which allow cell temperature regulation during any of the tests.

### **IR Lab**

The spectral response and spectral back surface reflectivity of the TPV cells are measured by the Standards Laboratory or the Infrared Technology group at JPL. Data can be taken across the spectral range over a range of cell temperatures. The IR Detector Lab is already well equipped to undertake TPV cell characterization -- the group does testing of several types of infrared detectors, with extensive experience at measuring narrow bandgap PV detectors in the 1 to 5 micron wavelength range. The equipment available includes variable temperature optical dewars, noise spectrum analyzers, grating spectrometers and a Fourier transform spectrometer (FTS). The FTS is used for spectral response measurements from 1 to 200 microns, with the option of measuring to 0.5 microns if necessary with an additional grating. It can also be configured to measure transmission or reflection of samples. Integrating spheres are also available for diffuse reflection and absorption measurements. Thus, comprehensive spectral response and back surface reflectivity testing for cell characterization would be completed at the IR lab.

Measurement of spectral back surface reflectivity of TPV cells has been proposed and may be attempted under the present test program. This may turn out to only require a simple modification of the test equipment and an additional grating. Spectral reflectivity and transmissibility of other TPV system optical surfaces may also be measured with the available laboratory equipment.

## **RAD Lab**

The JPL Radiation Effects Laboratory has been in existence for more than 20 years and has been used by many outside organizations, both commercial and government, as their primary source for this type of testing.

## **CONCLUSION**

A standard TPV cell characterization methodology would greatly benefit TPV technology development by providing a means of cell comparison and system modelling capability. Standards for characterization should now be considered to ensure complete and proper TPV cell testing. To accomplish this, there should be at least one facility capable of performing all of the tests to fully characterize a TPV cell.

Black body emission testing is necessary at different temperatures and intensities to acquire standard IV curves. The spectral response is necessary not only for cell power predictions, but is an vital element in understanding the effects of various environmental tests upon cell spectral response. Dark forward IV curves are needed to determine how much light generated current is lost due to the cell internal resistances. Light and dark reverse IV tests are needed determine the effects of cell breakage and subsequent cell heating. And finally, knowledge of temperature affects on these parameters is important.

Characterization over the full range of operating conditions is also necessary for accurate modelling of TPV performance losses. This would include testing of cell stability, cell durability, and radiation damage. This additional set of characterization testing accounts for realistic losses during TPV operation.

Lastly, the physical characteristics of a cell need to be measured for future comparison purposes.

All of the above tests, if performed for a cell, would then constitute TPV cell characterization, while selected subsets of these test can be used for material and cell quality assurance or for product improvement.

The JPL facility already has much of the necessary characterization equipment and laboratories including the LAPSS facility, the PV laboratory, the IR sensor laboratory and the Radiation effects laboratory.

## ACKNOWLEDGMENTS

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